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Linking household and productive use of electricity with mini-grid dimensioning and operation

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ABSTRACT

Off-grid systems, and mini-grids in particular, are expected to play a significant role in improving electricity access to one billion people until 2040. One of the major challenges for mini-grids is associated with their high costs, low financial viability and local development impact. Productive use of electricity can be an important driver of local development and impacts the total load in a mini-grid. By using a mixture of high-resolution (minutes) measurements and long-term data (years) on electricity expenditures and purchased electricity from a mini-grid in the Tanzanian highlands, we analyse the technical and economic impact from household and productive use of electricity, respectively. The high-resolution data is analysed using performance indicators and the long-term data using regression tools. We find that a mixture of household use and productive use of electricity provides both technical and economic benefits for the operator. In addition, we find that while productive use customers only represent 25% of the customers, they generate 44% of the operator's income. Furthermore, productive use of electricity customers are also likely responsible for the peak demand in the mini-grid, which occurs during day time. Lastly, we find empirical evidence suggesting that expenditures and demand are unit elastic, which has implications on economic policies for supporting rural electrification.

Introduction

Until 2040 one billion people are expected to receive access to electricity in developing countries (The World Bank, 2017). A majority of these people live in rural areas and will likely receive access through the use of off-grid technologies (Díaz, Arias, Peña, & Sandoval, 2010). Off-grid technologies can be divided into categories based on their generation capacity. The smallest commonly available range are SHS (Solar Home Systems), which are relatively cheap and can be afforded by many households. Due to their small size (both in terms of energy and power), SHS impacts are mainly focused on household activities (Gustavsson & Ellegård, 2004). In the mid-range are pico-systems. Unlike SHS, pico-systems are not independent solutions for single users, but technically interconnected through a distribution system. These systems can be based on a wide range of energy sources (hydropower being one common option) and have generation capacity in the order of 10 kW (Boait, Advani, & Gammon, 2015). Due to their size they can supply electricity to a small group of households and limited productive use activities. In the high range of the off-grid systems are mini-grids. Mini-grids have enough generation capacity to supply hundreds to a few thousand customers, including a wide range of productive use activities.

In order to make sure that the benefits of electricity are realised, the implemented solutions need to be affordable, reliable (International Energy Agency et al., 2018) and supply sufficient power and energy to its customers. An important factor to realize the economic and social benefits associated with electricity is through productive use (Cook, 2013; Peters, Harsdorff, & Ziegler, 2009). Productive use refers to the direct and indirect use of electricity to produce goods or services for the production of income or value (Cabraal, Barnes, & Agarwal, 2005). Through the creation of new business, refining of local resources and through the improvement of public services, productive use can contribute to improve both social and economic development. As such productive use of electricity includes commercial activities and public services. Due to the small generation capacity of SHS and pico-systems, the productive use in such systems is limited (Azimoh, Klintenberg, Wallin, Karlsson, & Mbohwa, 2016). Pico-systems, even though they have considerably larger capacity than SHS, still have small power outputs not sufficient for most productive uses. However, mini-grids have enough capacity to supply both small and medium sized business and public institutions (such as hospitals, schools and

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governmental offices) and thus have a potentially larger impact (Kirubi, Jacobson, Kammen, & Mills, 2009).

When mini-grids operate independently from the large national grids, they need to keep a constant supply and demand balance in order to maintain a high reliability. Furthermore, due to their relatively small size, the relative impact of individual customers behaviour is larger than in a large-scale power system. Due the often remote locations in rural electrification and low power consumption, renewable energy sources are preferred for generation (Blum, Sryantoro Wakeling, & Schmidt, 2013; Nguyen, 2007). In addition, the low and uncertain electricity consumption of individual customers and relative dispersed populations makes the dimensioning and operation of mini-grids difficult. Systems with too small generation capacity suffers from reliability issues, which impacts electricity benefits, operator economy and relationships between the local community and operator. If the systems are too large, unnecessary capacity cause high tariffs since construction cost of systems scales with their size (Zomers, 2003). Furthermore, funds are not often easily accessible and this impacts negatively on the diffusion of mini-grids. Knowledge about long-term growth in electricity usage is therefore important in order to keep mini-grids cost-effective and reliable. Richmond and Urpelainen (2019) found that appliance ownership grew slowly over time in rural India. Similarly, van de Walle, Ravallion, Mendiratta, and Koolwal (2017) found a small increase in electricity usage in rural India over 17 years. These studies suggest that electricity usage increase over time in rural areas, which impacts mini-grids sizing.

Previous research on the sizing of mini-grids have mostly been focused on technical and economic aspects (Haghighat Mamaghani, Avella Escandon, Najafi, Shirazi, & Rinaldi, 2016; S. Mandelli, Barbieri, Mereu, & Colombo, 2016). Furthermore, due to a general lack of data (Nfah, Ngundam, Vandenbergh, & Schmid, 2008; Terrado, Cabraal, & Mukherjee, 2008; Wang et al., 2020), many technical studies have relied on artificial data (Sen & Bhattacharyya, 2014). Artificial load profiles are often based on assumed electricity usage behaviour and might not represent actual behaviour. Using data from eight mini-grids in Kenya, (Blodgett, Dauenhauer, Louie, & Kickham, 2017) found that energy-use surveys overestimate electricity consumption with a factor of four. Similarly, doing an in-depth analysis of a mini-grid in Tanzania, (E. Hartvigsson & Ahlgren, 2018) showed that interview-based load profiles underestimate power demand, specifically during the night.

In addition to the long-term growth or decline of electricity demand, short-term variations (e.g. daily load profiles) also affect the sizing and operation of mini-grids. The impact of productive use on load profiles has been highlighted in the literature (S. C. Bhattacharyya, 2015; E. Hartvigsson, Stadler, & Cardoso, 2018; Ngowi, Bångens, & Ahlgren, 2019; F. Riva, Tognollo, Gardumi, & Colombo, 2018), but not tackled explicitly. In addition, variations in load profiles have been found to significantly affect mini-grid system dimensioning. Lozano, Querikiol, Abundo, and Bellotindos (2019) investigated the economics of off-grid electrification in Philippines and found that determining the system load profile was imperative for creating an economic sustainable system. F. Riva, Gardumi, Tognollo, and Colombo (2019) linked an energy demand and optimisation model for applications in rural India and found that optimal capacity varied up to 144% based on variations in electricity demand. Knowledge about electricity demand amongst different customer groups, and its impact on power demand, is therefore important in order to properly size mini-grids in rural areas. In addition, the mix of productive use and household use of electricity impacts mini-grids load profile, and thereby their operation.

However, none of the studies specifically analysed the impact of productive use of electricity on mini-grid dimensioning and operation. Thus, the purpose of this study is to add to the current literature on techno-economic assessments of mini-grids. This is achieved by analysing high-resolution measurements of power and long-term data series on electricity usage and expenditures from a hydropower mini-grid in south-western Tanzania. The study focus on load behaviour and purchase behaviour for households and productive use of electricity and their impact on the dimensioning and operation of the mini-grid. Specifically, the paper aims at answering the following question:

- What is the short- and long-term technical and economic impacts of household and productive use, respectively, on the dimensioning and operation of mini-grids?

The paper is outlined accordingly. First, we present our method followed by a description of the case. This is followed by results on electricity usage, performance metrics, income, and electricity expenditure data. The results are discussed and the paper ends with conclusions.

Method

In order to identify the contribution of productive and household use on the dimensioning and operation of mini-grids, we use long-term data on electricity usage, high-resolution measurements, and data on customer composition and tariff system. These two datasets include technical and economic aspects of electricity usage, but do not contain metadata on the mini-grids customers. The high-resolution data is used to calculate technical performance metrics. The long-term data is used to analyse trends in electricity consumption and electricity expenditures (income for the operator).

The high-resolution measurements are done using Amprobe 16-TRMS Pro current meters. The meters measures maximum, minimum and average current with a 5 Hz resolution and stores the values every minute for up to 3.5 days. The meters measures current; power is therefore estimated using nominal voltage (230 V for single phase customers and 400 V for three phase customers). Due to the limited number of current meters, measurements of electricity usage were only done at five different customers and at the hydropower plant, measurements at each location was done for 3.5 days. The measurements therefore represent a small sample of all customers and are primarily used to conceptualize differences in electricity usage. The five customers were: two households that belonged to a low consumption household group, two households that belonged to a high consumption household group and a small bar. Households are usually considered the largest load in mini-grids and are therefore important. A bar was chosen as they are common in villages and use more electricity than shops (mainly due to the existence of audio/video systems and fridges to cool drinks). Since measurements were only done on two households in each category it was important to capture variation within each category and within the mini-grid. The households were therefore chosen based on a discussion with mini-grid staff familiar with customers consumption levels. There are also a number of mills and workshops in the system, which consumption was estimated based on measurements in a nearby mini-grid (E. Hartvigsson et al., 2018). The millers in the two mini-grids had similar sized machines, charged similar prices and had similar mills/customers ratio. Thus, it is assumed that the millers and workshop have a similar behaviour in terms of electricity usage in the two mini-grids.

The measurements are used to calculate four technical performance metrics: daily electricity demand, peak power demand, load factor and capacity factor (for the entire mini-grid). The four indicators are commonly used within electric power systems for technically characterising demand and generation (Stern & Spencer, 2013). Specifically, they describe the relationship between power (design criteria of a power system) and electricity (income generation of an operator). Daily electricity demand E_{daily}, is calculated by integrating the measured current i, multiplied with the nominal voltage U_n and dividing with measured time t_{days}. No measurements on voltage fluctuations were done, and the nominal voltage is thus assumed to be fixed. Eq. 1 shows the general expression.

$$E_{daily} = \frac{\int_0^{t_{days}} U_n \cdot i \, dt}{t_{days}} \quad (1)$$

In order to accurately calculate a systems capacity factor, long time series of high-resolution data are needed. Since high-resolution data only was available for a short time period and the long-term data lacks resolution, two approaches to capacity factor calculations are presented. The first approach uses the high-resolution data to calculate an accurate capacity factor for the measured days. The second approach use the long-term data to calculate the annual capacity factor. Eq. 2 shows the general expression for calculating a capacity according to approach one, while Eq. 3 shows the general expression for calculating the capacity factor according to approach two. For the short-term capacity factor (Capacity $\text{Factor}_{\text{short}}$), P_L is the load at time t, and T_{short} is the measurement time. For the long-term capacity factor (Capacity $\text{Factor}_{\text{long}}$), E_j is the electricity sold in month j, k is the total number of months, and T_{long} is the time-frame.

$$\text{Capacity Factor}_{\text{short}} = \frac{\int_0^{T_{short}} P_L(t) dt}{P_G \cdot T_{short}} \quad (2)$$

$$\text{Capacity Factor}_{\text{long}} = \frac{\sum_{j=0}^{k} E_j}{P_G \cdot T_{long}} \quad (3)$$

The peak load in a system is the maximum power demand recorded over a specific time period. It is the minimum power that a system must to be able to supply in order to fulfil demand at all times. The time period (T) used to record the peak load was 3.5 days, see Eq. 4.

$$\text{Peak load} = \max(P_{L,T}) \quad (4)$$

Load factor is an indicator of the variation of load and can be used to describe the spiky behaviour of electricity demand. A higher load factor equals small variations and is often preferred from a techno-economic perspective. Eq. (5) shows the general expression for calculating the load factor. $P_{L,\ Avg}$ is the average load and $P_{L,\ Peak}$ is the maximum measured (or generated) load.

$$\text{Load Factor} = \frac{P_{L,Avg}}{P_{L,Peak}} \quad (5)$$

The long-term data was extracted from the mini-grid's computerized payment system. The system is to a large extent automated. In order to separate the impacts from households and productive use customers data is separated for each user group (households and productive use). The long-term dataset contains data on purchased electricity (kWh) and electricity expenditures (Tanzanian shillings, TZS) for each customer, but do not contain customer metadata. The data is used to identify long-term trends in electricity expenditures and purchased electricity and was collected between March 2013 to January 2017. Due to technical issues with the prepaid system, data was unavailable for a total of 3 months during the time period. Since data is collected on a per customer basis, and since customers often purchase electricity in bulk, the data needs to be processed in order to identify long-term trends. The data is processed separately for households and productive users and for electricity expenditures (Tanzanian shillings, TZS) and electricity purchased (kWh) using the same processing method. Annual inflation values are taken from The World Bank (2019), and costs are shown in 2017 TZS. Data for each individual customer is averaged on a monthly basis using a moving average. A monthly average is then calculated based on the contribution of each customer. Eq. 6 shows a general expression for the calculation of the monthly contributions.

$$C_{g,m} = \frac{1}{k}\sum_{j=1}^{k}\frac{1}{M}\sum_{m=1+l/2}^{M-l/2}\frac{P_{m-l/2} + .. + P_m + .. + P_{m+l/2}}{l} \quad (6)$$

where g is the customer group (household or productive use) m is the month, M is the total number of months, k is the number of customers making a payment that month, l is the moving average window length and P is the registered expenditure or amount of electricity. In order to identify long-term trends, linear and non-linear regression models are generated from the processed data. Based on expected behaviour of the data, polynomials (increase and/or decrease) and trigonometric (seasonal variations) functions are considered.

The case

The analysis is conducted on a community based mini-grid set up by the Italian NGO ACRA, in south-western Tanzania. The mini-grid is supplied by a small-scale hydropower plant and does not have a grid connection. The hydropower plant consists of two 150 kW Pelton turbines and supplied (as of January 2017) 1544 customers. According to the initial plans ACRA handed over the operation to a local community-based organization in 2014, which has been in charge of operation and maintenance since. The system is situated in the highlands with a subtropical highland climate and covers five villages. Most households engage in farming (with maize being a common crop). In addition, there are also a number of productive use activities including welding, milling, workshops hospitals and schools. As part of the project, ACRA encouraged productive use activities through various supportive mechanisms.

The mini-grid was constructed by ACRA and was brought online in 2010. Initially the system used a flat tariff system but in 2014 the system changed to a pre-paid system with five tariff groups based on customers expected consumption. The pre-paid system is automated using credit-based meters. Credits can be bought in multiple locations in the connected villages. In addition to the cost per kWh, each customer has to pay a monthly service fee. Customers were classified into five tariff groups (see Table 1) based on their consumption. The five different tariff groups are divided accordingly: two for households, one for public institutions and small businesses, one for mills and one for other large machines and small industries). Each category has a fixed monthly service charge and an electricity tariff.

Customer assigned to tariff group 1 has a low expected electricity use, limited number of appliances, but has also a low price per kilowatt-hour. The tariff and service fee increase for each group. As both the tariff and service fee has been subject to multiple changes,

Table 1
The five different tariff groups with corresponding descriptions.

Households		Productive use		
Tariff group 1	Tariff group 2	Tariff group 3	Tariff group 4	Tariff group 5
Low consuming households (1–7 power points)	High consuming households (8 or more power points)	Small business and public institutions	Mills	Small industries

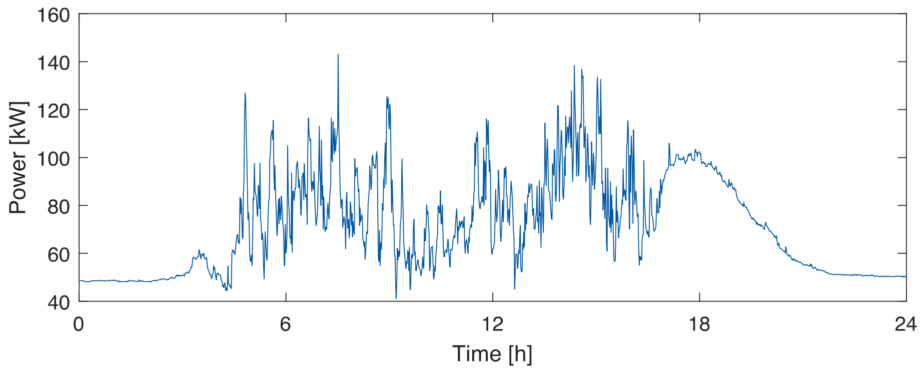

Fig. 1. Load profile of the entire mini-grid during a weekday.

they are excluded from the table. The customers are also separated into households (tariff group 1 and 2) and productive users (tariff group 3, 4 and 5). Due to data sensitivity, tariff values are not published.

Results

Performance metrics

Measured load profiles from the different customers are presented in Fig. 1-3. This is followed by calculated performance metrics for each of the load profiles. Data on electricity purchased and expenditures are presented followed by income from the various usage types. Fig. 1 shows a measured load profile of the entire mini-grid. The figure shows a constant night load of roughly 50 kW, a high day load that consist of many rapid and large fluctuations and finally an evening peak. The peak load is 143 kW and takes place during the day while the evening demand is roughly 100 kW.

Fig. 2 shows measured load profiles of the households. The households in the top graphs belongs to tariff group 1 (household 1a and 1b) and the households in the bottom belongs to tariff group 2 (household 2a and 2b). There are large differences between all four households. Household 1a and 2a show similar electricity usage despite being in separate tariff groups. Household 1b shows a very low electricity usage and power demand. Household 2b shows a very high peak, which is likely caused by either a heater or cooker.

Fig. 3 shows measured load profiles for the productive uses of electricity. The top left graph shows measurements from a bar, the top right graph from a workshop and the bottom two graphs from millers. The productive use activities have a higher electricity consumption and power demand during the day when compared to the households. The bar is characterized by a comparably flat load profile during its opening hours. The mills and workshop are characterized by very high peak loads with periods of very low loads.

Table 2 shows performance metrics calculated from the measurements presented in Figs. 1, 2 and 3. According to the performance metrics there are large variations between the customers. Electricity consumption varies with a factor 3 between the households. Peak load varies with a factor of 31 and load factor with a factor of 16. For the productive use activities, the small bar shows considerably lower peak load and electricity consumption than the mills and workshop. However,

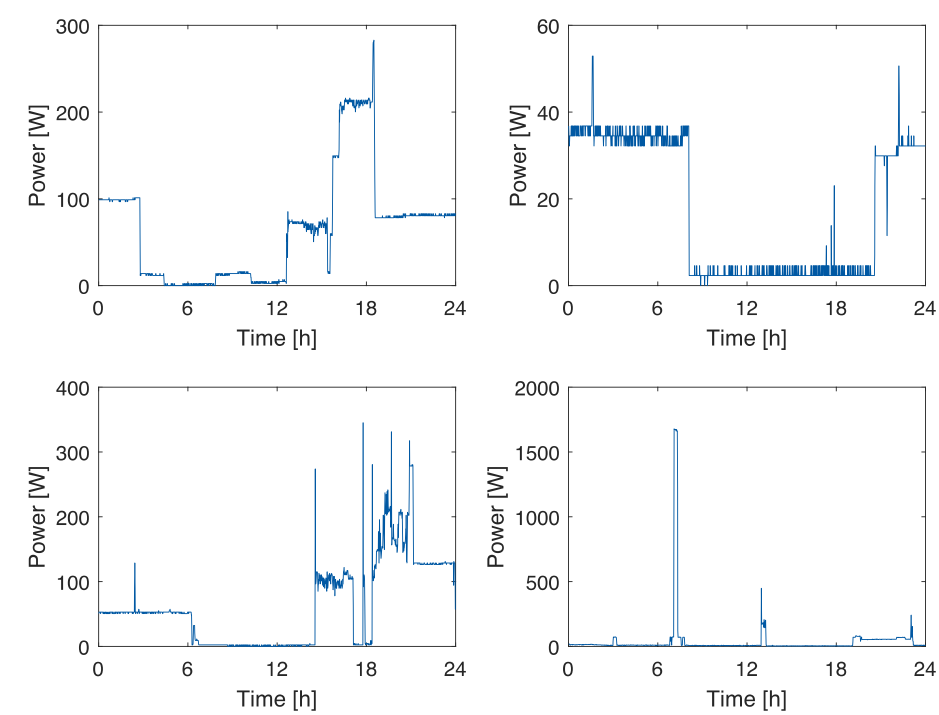

Fig. 2. Load profiles of household use. Top two figures show load profiles for low-consuming households in tariff group 1. Bottom two figures show load profiles for high-consuming households in tariff group 2.

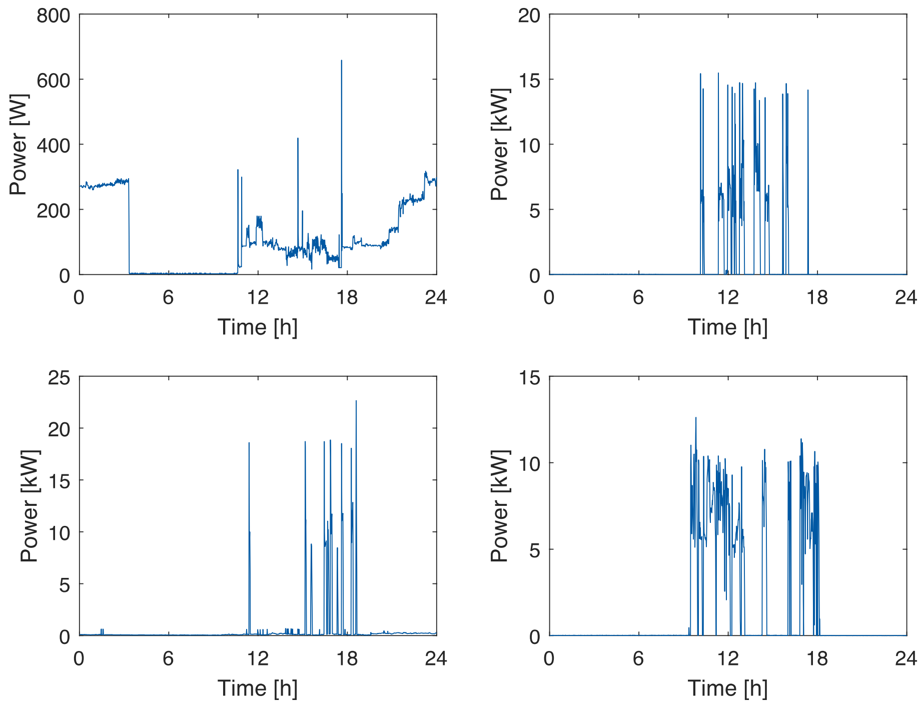

Fig. 3. Load profiles for productive use of electricity. Top left figure shows a load profiles for a bar. The top right figure shows a load profile for a workshop and bottom load profiles show electricity use for mills. The load profiles for the workshop and mills were taken at a nearby village.

load factors are more similar. All productive use activities show a considerably higher daily electricity consumption than the households, and in most cases lower load factors.

Trends in electricity purchased and electricity expenditures

Figs. 4 and 5 shows data on amount of electricity purchased and electricity expenditures, for households (Fig. 4) and productive users (Fig. 5). The figures contain results from the regression models (linear and trigonometric with linear growth) and processed data in order to clarify long-term trends. The periodic function with linear growth shows the best fit (higher R-squared and lower Root Mean Square Percentage Error) in all instances. Seasonal variations in income due to a large reliance on farming is expected to result in period behaviour in electricity expenditure. However, electricity expenditures show less periodic variations compared to electricity purchased, and a stronger linear relationship for both households (R-square of 0.88 compared to 0.5) and productive users (R-square of 0.69 vs 0.2). Electricity expenditures shows a significant growth for both households and productive users, with average increases of 280% and 135% respectively over the 30 months period studied. Similarly, electricity purchased shows a growth of 56% for households and 37% for productive use customers.

Table 3 shows the distribution of customers and the share of operator income. The productive users are further divided into smaller productive users (Tariff group 4) and large productive users (tariff group 4 and 5). As is seen in Table 4, the majority of customers are households (75%) compared to productive use (25%). In addition, the large productive users constitute a very small part of the total customers (4%). Even though productive use only represents 25% of the customers, they are responsible for 44% of the income.

Table 4 shows statistical parameters for the data shown in Figs. 4 and 5. As shown in the Table, electricity expenditure values show a significant standard deviation. Similarly, the standard variation in electricity purchased is also very large, both for households and productive users. This suggests that additional classification based on electricity purchased or electricity expenditures could be relevant. The table also shows that productive users on average purchase almost three times the electricity compared to households.

Table 2
Performance metrics for each of the load profiles shown in Figs. 1, 2 and 3.

	Peak load (kW)	Daily electricity consumption (kWh)	Load factor	Capacity factor
Mini-grid	143	1722	0.50	0.24
Household 1a	0.280	1.6	0.24	–
Household 1b	0.05	0.4	0.33	–
Household 2a	0.345	1.5	0.18	–
Household 2b	1.68	0.93	0.02	–
Small bar	0.685	1.92	0.11	–
Miller 1	22.7	14	0.03	–
Miller 2	12.7	37	0.12	–
Workshop	15.5	18	0.05	–

Discussion

Performance metrics

Using high-resolution load profiles and long-term data on electricity purchased and electricity expenditures, we have analysed technical and economic impacts of electricity usage. Due to the technical difficulties in collecting high-resolution measurements, the electricity load profiles were measured at four households and one bar. The generalizability of the measurements for the entire mini-grid is therefore limited. In-terms of daily electricity usage, they are similar to electricity usage in Rwanda (Kojima et al., 2016) but lower than electricity usage in a similar mini-grid in Tanzania (E. Hartvigsson et al., 2018). Differences are likely due to variations between households, applied payment systems of the different systems and daily variations. Even though the measured customers are few, they showcase conceptual similarities and

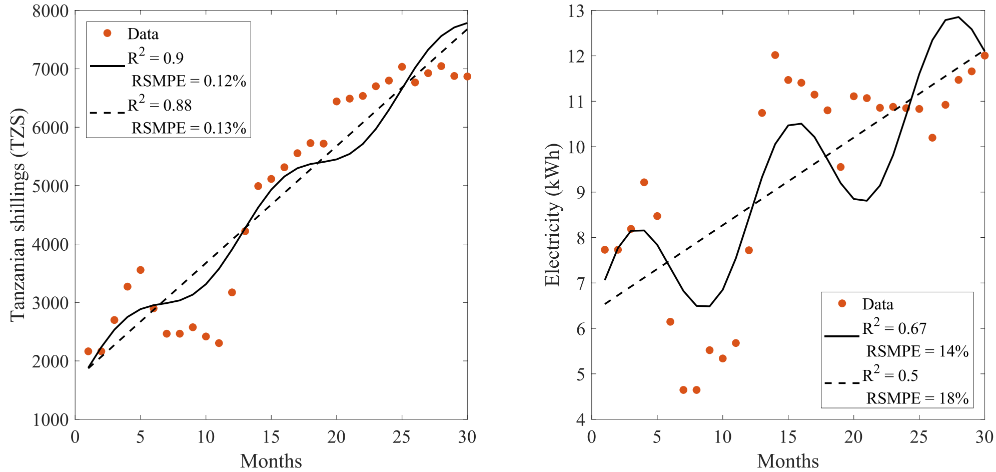

Fig. 4. Averaged data and least-squares regression models for households. Left graph shows results for electricity expenditures per month and customer and right graph electricity purchased per customer and month.

differences important when sizing mini-grids. Household electricity is likely to be concentrated in the morning and evening, similar to some productive use (such as bars) but have a large variation in their electricity and power usage. The bars electricity usage is likely associated with its opening hours. However, high powered productive uses (such as milling) is more likely to be concentrated during daytime.

The performance metrics from the households reveal that there is considerable variation amongst the households, both in terms of electricity consumed and power demand. The lowest consuming household has the highest load factor. Even though Household 1a and 2a belong to different tariff groups, they have similar load factors and electricity consumption. Household 2b has similar electricity consumption to Household 1a and 2b but a much lower load factor due to a higher peak load. The high peak load is likely due to the use of a cooker/heater. Amongst the measured households, all show a decrease of load factor as electricity consumption increase. If the likelihood of power demand occurring simultaneously for the high consuming households is high, it would be desirable to have more low consumer households than high consuming households in order to flatten the load profile. Overall, it is seen that household's contribution to the overall load profile is mostly in the evening and night, with a smaller contribution during the day mainly attributed to the high consuming households.

The different productive use activities show significantly different load profiles. As is expected, the mills and workshop have a very erratic behaviour with very high peak loads followed by no load at all, or a very low load. In total, there are 22 mills in the system (and an additional 33 small industries). As their operation is mainly during the day, it is likely that these customers are responsible for the daily spikes in demand seen in Fig. 1. The load profile for the bar, shows a relatively constant load during the day, with a smaller increase in the evening. The load factor, peak demand and daily electricity demand for the bar distinguish it from the households, the mills and the workshop. The bars flat daily load is likely comparable to other similar customers (e.g. restaurants or shops) but with the reduced power demand occurring at slightly different times, based on their respective opening hours. According to Table 4, these small productive users are relatively many and are therefore likely responsible for the bulk load during the day.

As shown by the measurements in Fig. 1, the peak load of the system occurs during the day and is significantly larger than the evening peak (35%). Many mini-grid sizing studies rely on load profiles with a large evening peak (Bekele & Tadesse, 2012; S. Mandelli, Brivio,

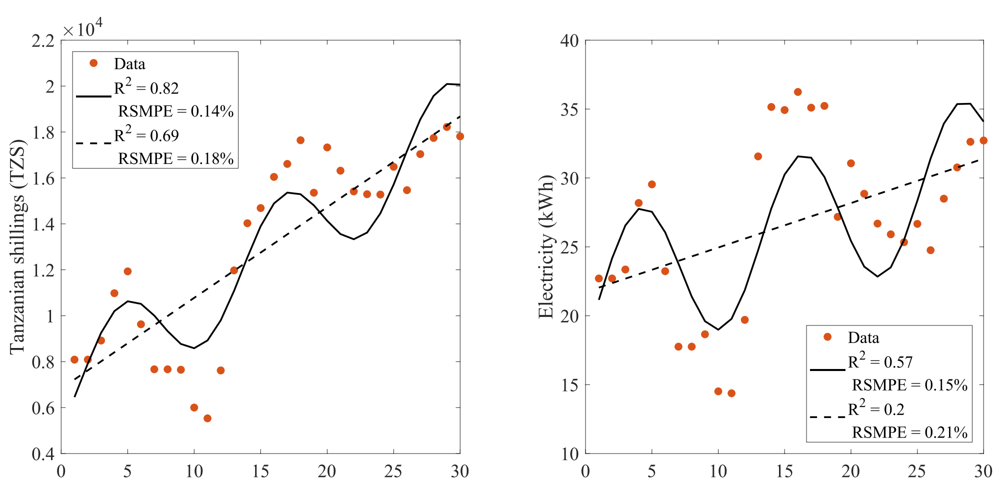

Fig. 5. Averaged data and least squares regression models for productive users. Left graph shows results for electricity expenditures per month and customer and right graph electricity purchased per customer and month.

Table 3
Number of customers belonging to the respective three customer groups. Percentage might not add up due to rounding errors.

	Households	Small productive users	Large productive users (e.g. millers and small industries)
No. customers	1145	344	55
Fraction of total users (%)	75	22	4
Share of operator income (%)	56	44	

Colombo, & Merlo, 2016), or no/very low evening demand (Kenfack et al., 2009). As productive use activities are mainly focused around the day, these studies thus exclude the potential technical and economic impact of either productive use or household customers. The high electricity consumption shown in Fig. 1 indicates the high share of productive use in the system. The peak demand (143 kW) is also considerably less than the installed peak generation capacity of 300 kW. Thus, there is significant available capacity to increase consumption, either for existing customer to increase their consumption or by connecting additional customers. However, it should be noted that daily and seasonal variations will likely impact the peak load, and the annual peak load could be higher. The reported capacity factor and load factor are similar to those reported by The World Bank (2005) and Bhattacharyya (2015). This suggests that if productive use activities are encouraged, mini-grids can be sized to handle a diverse system with a high load factor.

Trends in electricity purchased and electricity expenditures

As seen in all graphs in Fig. 4, electricity expenditures and electricity purchased increased for both household customer and productive use customers during the time. Yet, compared to national household electricity consumption, it is very low (Shibano & Mogi, 2020). The low annual electricity consumption is likely due to low income levels and lack of access to electric appliances. During the development of the project, ACRA invested significant time and resources to educate and highlight the benefits of electricity, which has likely had a positive impact on electricity expenditures and purchased electricity growth. Overall, both the households and productive user's regression curves shows better fit for electricity expenditures than amount of electricity bought. In addition, both the household and productive use expenditures show an increasing trend. Between month 14 and 15, the tariff was increased by 52–62% for all customers. No equivalent increase in electricity expenditure can be seen in Figs. 4 and 5. For households, there seem to be no impact on electricity expenditures, while productive users shows a smaller increase in electricity expenditures. However, it is uncertain whether this latter increase is due to periodic behaviour in electricity expenditures or due to tariff changes. The lack of large trend changes in electricity expenditures following the increase in household tariffs suggests that for households, electricity expenditures and electricity demand are close to unit elastic. A price demand elasticity of close to one means that customers responds to increase in price by reducing their demand. This can have significant implications for the operator, as raising electricity tariffs would result in a decrease in purchased electricity, potentially offsetting an increase in operator income.

The productive use activities show stronger periodic behaviour compared to households. The periodic behaviour of productive use activities can partly be linked to the milling and small industrial businesses. Many of the income generating activities in the villages are agriculture related and it is reasonable that these activities are more intense (thus using more electricity) during harvest seasons. In addition, as shown by Gabrielsson, Brogaard, and Jerneck (2013), household expenditures are seasonal and due to factors such as school fees and harvest. As such, households might increase their expenditures on the goods and services produced by the productive users related to the harvest season. However, the small periodic variations amongst households electricity expenditures may seem surprising given the seasonal dependency of other expenditures (Gabrielsson et al., 2013). A possible explanation is that electricity is prioritized compared to other expenditures, or that electricity expenditures is low, compared to overall household expenditures.

For households, there is less variation in electricity expenditures than electricity purchased. Compared to households, productive use shows to a larger extent periodic variation in both electricity expenditures and electricity purchased. As the economic development status in the mini-grid is low, it is reasonable that household customers are price sensitive, thus reducing the electricity purchased rather than increasing their expenditures. Similar to our findings, price elasticity of demand for energy was reported by De Vita, Endresen, and Hunt (2006) for a number of sub-Saharan African countries, ranging from −0.863 to −0.97. De Vita et al. also found that price elasticity of demand for energy is lower in sub-Saharan Africa than in other developing regions.

As seen in Table 3, the operator's income is roughly equally divided between household and productive use. However, productive use customers only represent a small share (26%) of total customers. Productive use customers therefore have a substantial individual impact on mini-grid operator's income. Since mini-grids in rural electrification often struggle with economic related issues (Greacen, 2004; Kirubi et al., 2009), increasing income flows without having to increase the power output of the generation system would have positive impacts on mini-grids economic viability. Thus, in a system with no, or limited electricity supplied to productive use and with available power, the marginal income of increasing productive users is high. The marginal income may be especially high in mini-grids based on renewable electricity sources, which generally have low operational costs.

Conclusions

Using high-resolution measurements and three year data on electricity expenditures and purchased electricity, we have conducted a techno-economic analysis of household customers and productive user customers in a mini-grid in Tanzania. The peak load in the system occurs during the day, is approximately 35% larger than the evening peak and is likely due to the large share of productive use customers in the system. The share of productive use customers in the mini-grid is around 26% but responsible for 44% of the income. We have found that the load profiles from household customers and productive customers complement each other well but have large individual variation. The large discrepancies between different household customers are reflected both in term of electricity consumption and power demand. For household customers, load factors tend to decrease with an increase in electricity consumption.

Both household and productive use customers showed a significant increase in expenditures and electricity purchased during the studied time-period. Periodic variation in electricity expenditures were larger for productive users compared to households, while both showed strong periodic variations in electricity purchased. We also found evidence suggesting that electricity price demand is close to unit elastic.

Table 4
Statistical parameters of the data shown in Figs. 4 and 5.

	Electricity expenditures (TZS)		Electricity purchased (kWh)	
	Mean	Standard deviation	Mean	Standard deviation
Households	3000	2500	7.0	10.3
Productive use	8200	1800	20.0	48.8

An increase in electricity tariffs might therefore not result in a corresponding increase in operator income. These findings are important for mini-grid operators. It can guide them in the process of sizing mini-grids based on the ratio between household and productive use customers and the corresponding impacts on their income. It also highlights the economic and technical importance of including, and supporting the further addition of, productive use customers in mini-grids.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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